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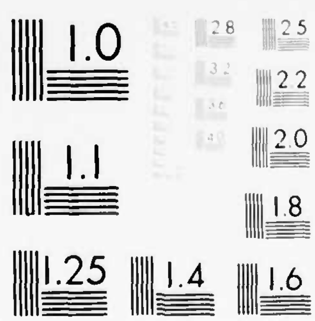

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State Water Survey Division
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THE EFFECT OF SPATIAL VARIABILITY IN PRECIPITATION ON STREAMFLOW

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Technical Report 6
NSF Grant ATM 78-08865
Low Level Convergence and the Prediction of Convective Precipitation
September 1981

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In most approaches to modelling the rainfall/runoff process, a spatially lumped description of precipitation has been assumed adequate for modelling the important aspects of catchment response. However, theories of catchment hydrology as well as some recent modelling studies suggest that spatial variability in precipitation may be important in determining the characteristics of streamflow hydrographs. Data from two intensive rainfall recording experiments in Illinois have been used to examine the effects of rainfall pattern on stream hydrographs for

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20. ABSTRACT CONTINUED

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ABSTRACT

In most approaches to modelling the rainfall/runoff process, a spatially lumped description of precipitation has been assumed adequate for modelling the important aspects of catchment response. However, theories of catchment hydrology as well as some recent modelling studies suggest that spatial variability in precipitation may be important in determining the characteristics of streamflow hydrographs. Data from two intensive rainfall recording experiments in Illinois have been used to examine the effects of rainfall pattern on stream hydrographs for summer convective storms. A threshold analysis was used to distinguish storms of markedly different pattern. A mixed deterministic/stochastic modelling procedure was used to determine the length of record required to differentiate the hydrograph characteristics resulting from storms of different patterns. It was found that differences in peak timing were highly significant but that differences in the distributions of peak flow and stormflow volumes were generally insignificant even given a long period of record.

INTRODUCTION

An accurate assessment of the spatial pattern of precipitation delivered to the surface of a catchment may be important for rainfall/runoff modelling from two viewpoints. First, derivation of a useable estimate of the total volume of storm precipitation for a basin may require that the spatial distribution of rainfall be taken into account. The question of spatial variation in this case is related to the sampling problem for rainfall, i.e., to the question of how many raingages are required to achieve a certain level of confidence in runoff prediction. The second aspect of the spatial pattern problem is the question of whether, or to how great an extent, spatial variability in precipitation, in and of itself, affects measurable attributes of stream hydrographs given that, in an actual hydrological record, other sources of error, uncertainty and spatial variation may obscure any relationship.

The influence of rainfall variability on simulated streamflow has been approached primarily with the rainfall sampling problem in mind. Dawdy and Bergman (1969) concluded that errors in estimating precipitation volume and intensity over a catchment were likely to be the factor limiting the accuracy of runoff simulation in most cases. Phanartzis (1972) demonstrated the importance of incorporating an altitudinal pattern in precipitation in simulating runoff from a watershed in the San Dimas Experimental Forest. Wilson et al. (1978) compared

simulated hydrographs generated using a distributed rainfall input with those generated using rainfall for a single gage for the same storm. They concluded that errors in the estimation of precipitation input may result in serious errors in predicted runoff hydrographs. On the other hand, Chow (1978) concluded that a single raingage input was sufficient for establishing a relationship between monthly precipitation and monthly streamflow for the Sangamon River in Illinois.

In this paper we examine the importance of spatial variability in precipitation from both the standpoint of the sampling problem and the problem of isolating effects of spatial precipitation patterns from a noisy record. The problem was investigated for a particular case study - a catchment in central Illinois - as part of the VIN project, a meteorological experiment carried out in central Illinois by the University of Virginia, the Illinois State Water Survey (ISWS) and the National Hurricane and Experimental Meteorology Laboratory. Data from this experiment and from earlier experiments conducted by ISWS were used to examine the effects of rainfall pattern of summer storms on stream hydrographs. A deterministic/statistical modelling procedure was used to estimate the relationshio between length of record available and the level of confidence attached to the differentiation of differences in hydrograph characteristics resulting from storms of different patterns.

AVAILABLE DATA

Data from the VIN experiment were collected during July and August of 1979. Rainfall measurements at a frequency of 5 minutes from an array of gages (see Fig. 1) spaced at approximately 5 km intervals were available. Bihourly streamflow data for Friends Creek, a catchment of 287 km^2, were provided by the USGS. The Friends Creek catchment is outlined on Fig. 1.

Precipitation data for the East Central Illinois Network (ECIN), which was operated by the ISWS during summer periods for 12 years beginning in 1955, were made available to us by ISWS. Information on the characteristics of the network and on the time/space patterns of rainfall observed in the ECIN network are given in Huff (1967, 1968). Stream gage records for the 1955-1958 period for Goose Creek, a catchment of 122 km^2 within ECIN, were obtained from the USGS.

THRESHOLD ANALYSIS OF ECIN/GOOSE CREEK DATA

The threshold analysis used in this study is an attempt to separate the effects of spatial variability of convective precipitation on storm runoff from the many other influences on catchment response, such as intensity and duration of storm precipitation and the pattern of antecedent moisture conditions over the catchment. The concept is to separate the events in the rainfall record into several categories

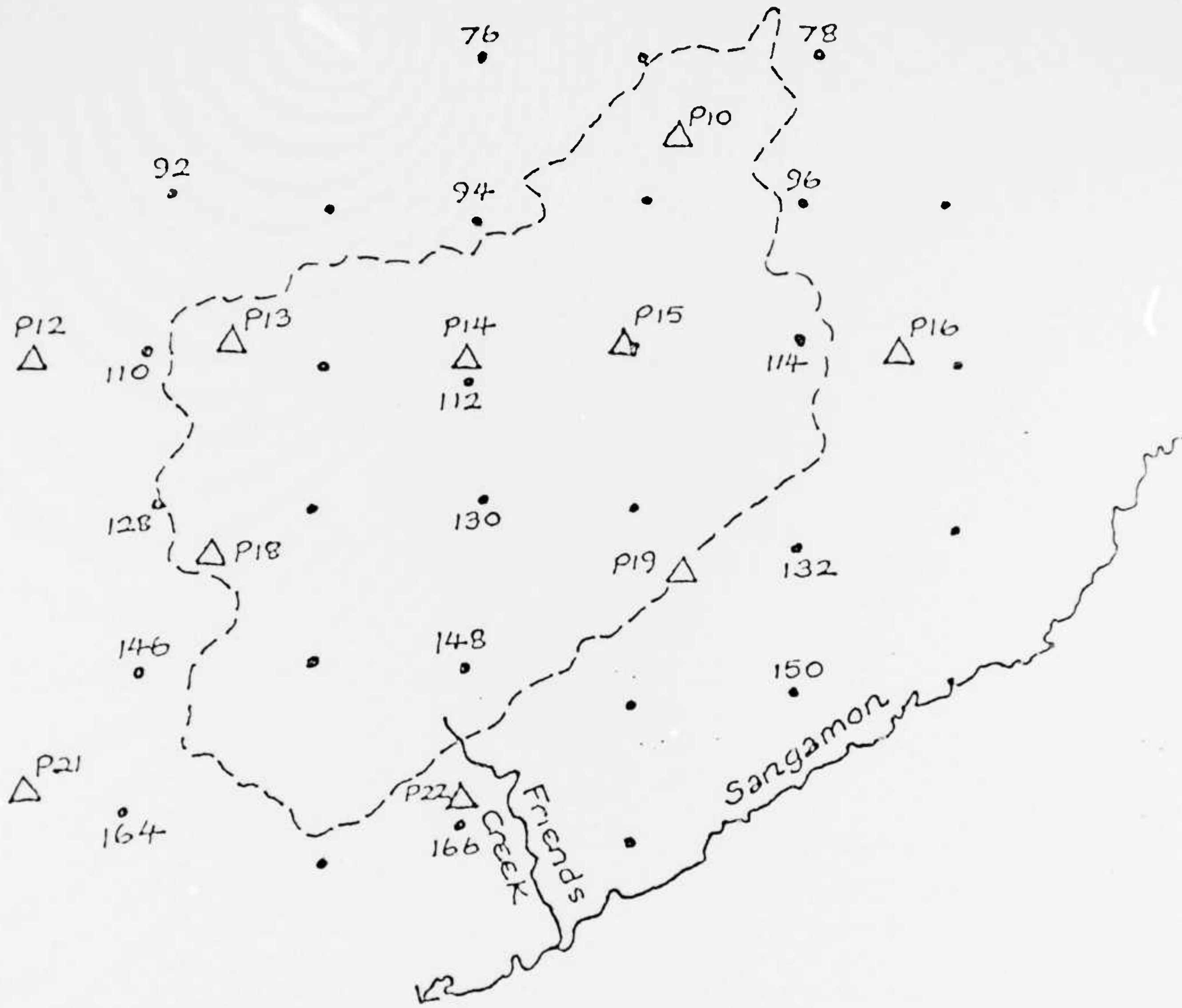


Figure 1. The raingage network for the Friends Creek catchment.

based on the pattern of storm precipitation, and then to use simple statistical techniques to test the hypothesis that rainfall pattern has a significant effect on the characteristics of the resultant hydrographs. The initial analysis was carried out using the ECIN/Goose Creek data in the summers (June to August) of the overlap years 1955/58. This gave a sample of 156 rainstorms for analysis.

The separation procedure used is shown schematically in Fig. 2. The procedure accepts average storm precipitation from three subcatchments of the basin. On the basis of a catchment area/distance from outlet histogram, three subcatchments of equal area were defined. Average storm precipitation in each subcatchment was calculated by multiplying the gage totals by appropriate Thiessen polygon weighting factors. Suitable values of the threshold parameters were found to be TH1=1.25, TH2=5.0 mm, TH3=0.2 and TH4=5.0 mm. It was found that storms showing distinct spatial patterns in total storm rainfall (the temporal distribution at each site was not available) were relatively rare. Only 5 useable storms were separated into category 1 and 5 in category 2. These storms, together with the characteristics of the associated hydrographs are shown in Table 1. Given this sample size none of the characteristics were statistically different. Mean values of average catchment precipitation, delay time and rise time for the two categories were very close. Any differences that there may be in the response of the two categories are obscured by differences in other factors.

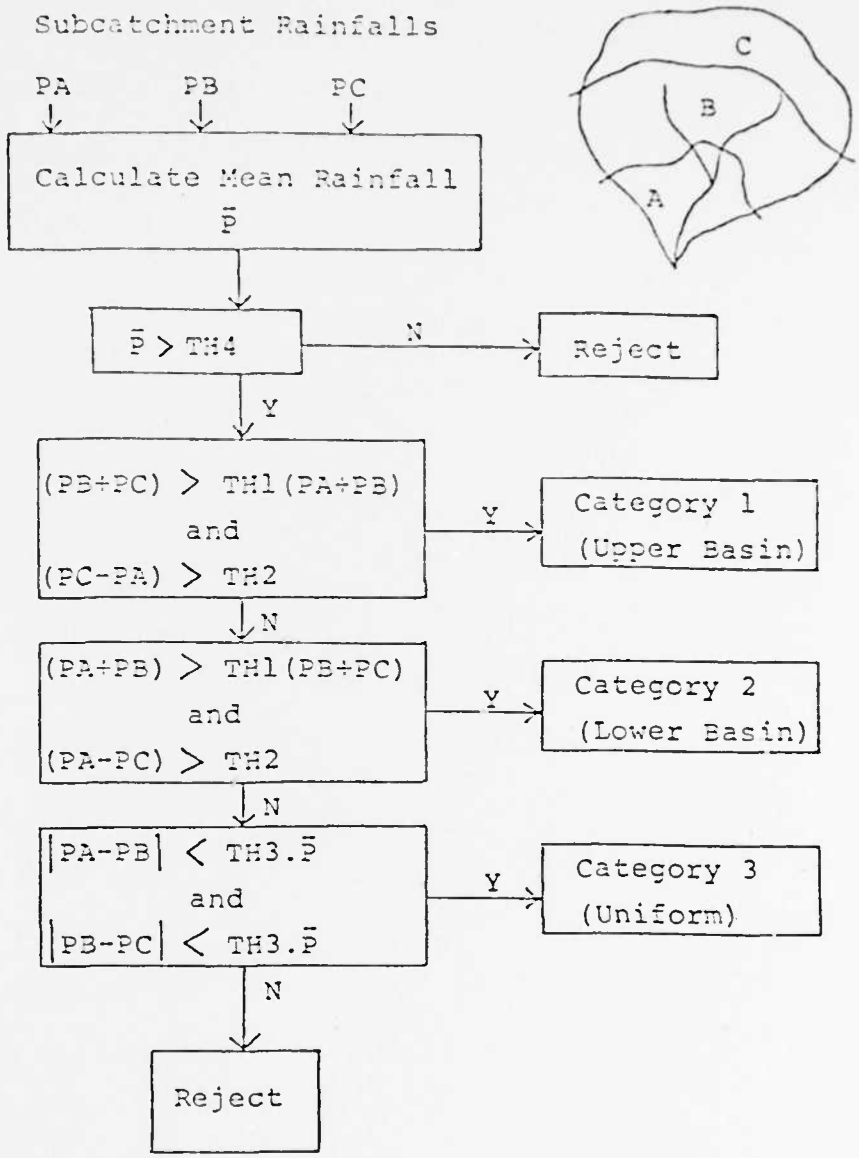


Figure 2. Algorithm for the threshold analysis.

TABLE 1. Selected rainfall and hydrograph characteristics for storms in which the precipitation was highest on the upper basin (Category 1) and those for which the highest precipitation was on the lower basin (Category 2).

Date of Storm	Average Rainfall (in)	Antecedent Stage (ft)	Peak Stage (ft)	Delay Time (hr)*	Rise Time (hr)**
Category 1					
5 Jun 55	0.51	1.14	2.48	2.0	3
22 Jun 56	0.50	1.36	2.19	0.5	2.5
18 Jun 57	0.37	2.50	3.22	0.0	6
13 Jul 57	1.15	1.40	1.97	2.2	3
7 Aug 58	0.68	2.62	3.76	9.1	2
Category 2					
3 Aug 56	0.53	0.57	3.93	0.0	4
30 Aug 56	0.42	0.35	0.45	1.2	4.5
17 Jun 57	0.24	2.45	2.79	0.0	1
17 Jun 58	0.75	2.88	6.06	4.9	4
19 Jun 58	0.22	3.24	3.73	7.0	3

*Defined as the time of initial increase in stage minus the average time of initiation of precipitation at raingages within the catchment.

**Defined as the time of first noticable change in the rate hydrograph rise minus the time of initial increase in stage.

A SIMPLE DISTRIBUTED RAINFALL/RUNOFF MODEL

The discussion above suggested that given the data base available from the ECIN/Goose Creek measurements, it would not be possible to draw any firm conclusions regarding the importance of knowledge of the spatial variability of rainfall inputs to predicting storm discharges. The implication is that the four summers of rainfall/discharge data available for the Goose Creek catchment are not sufficient to distinguish the effect of rainfall pattern from other factors such as antecedant moisture conditions, storm durations and intensities. Consequently a somewhat modified question was examined. How long a period of record would be necessary before the effect of spatial variability could be demonstrated to be statistically significant? To make a first estimate of the length of data required a deterministic/statistical simulation approach was adopted.

The steps in the analysis are shown in Fig. 3. The validity of the analysis depends largely on the quality and quantity of the data available for calibration of the rainfall and rainfall/runoff models used. The best data available for the rainfall/runoff calibration were the VIN/Friends Creek data collected during the summer of 1979. Five minute rainfalls and bihourly streamflow data were available. However, the discharge record during this relatively dry summer was dominated by a single storm hydrograph, preceded by two smaller hydrographs as the

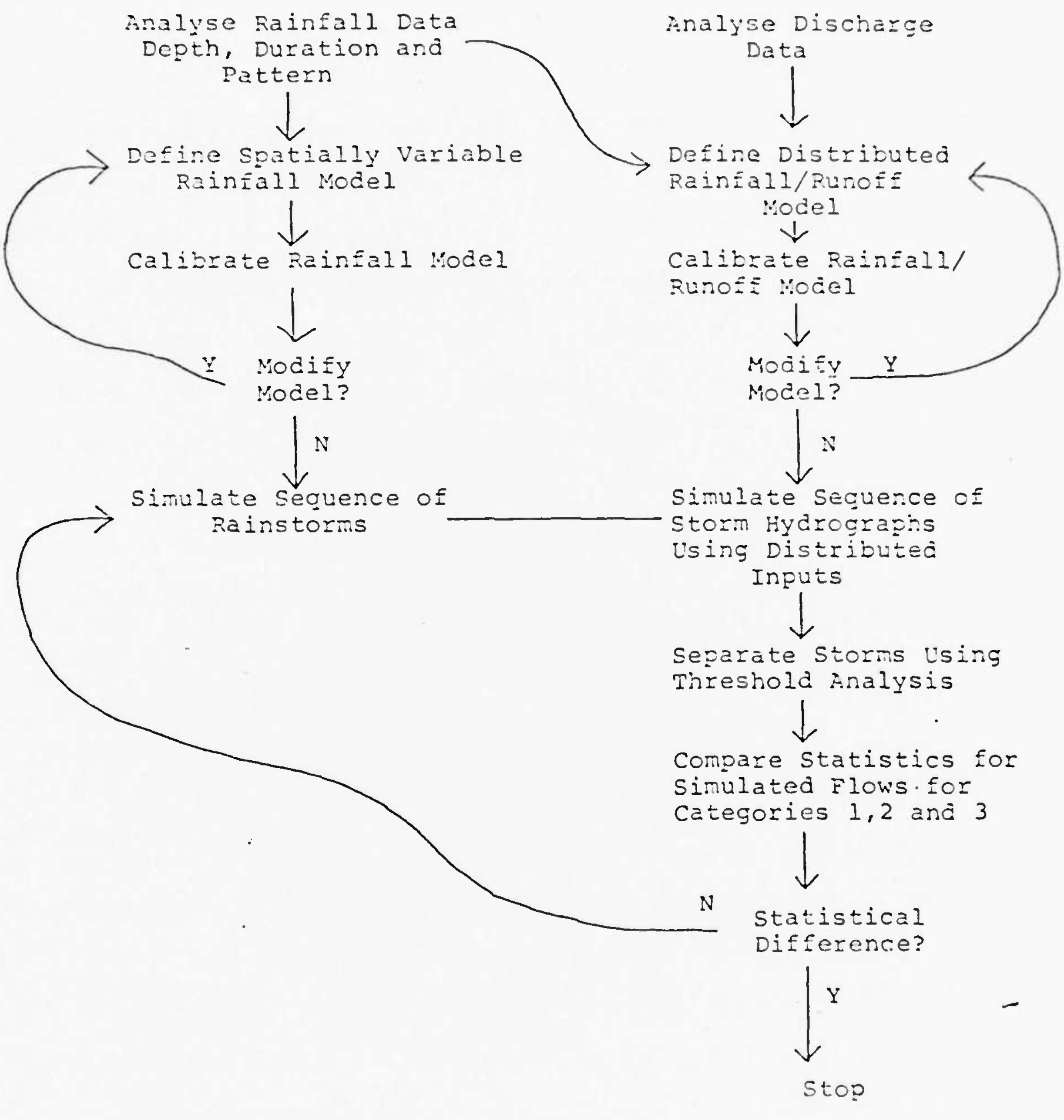


Figure 3. Diagram of the deterministic/statistical modelling procedure.

catchment wetted up during the end of July and beginning of August. The previous hydrograph peak of any significance was on April 26, 1979.

It was clear that this data base would not support calibration of any complex rainfall/runoff model. A number of simple deterministic distributed models were investigated but the final choice was the simplest of all. This model is shown schematically in Fig. 4 and consisted of a number of subcatchment models contributing to a constant wave speed (linear channel) channel routing component similar to that used by Surkan (1969) and Kirkby (1976).

The subcatchment model consists of two storage elements. The store S1 is associated with two threshold parameters: one (Sc) controlling discharge from a riparian contributing area Ac; the other (Sd) controlling input to the S2 store. Various non-linear forms were tried for the S2 store, but early runs showed that a simple linear formulation was satisfactory. Evaporation was taken from the S1 store at the measured pan potential rate (available on a daily basis) until the store was empty.

The channel routing procedure is equivalent to a constant time lag for each incremental length of the channel network. Input per unit area in each subcatchment is assumed constant at each time step. Total catchment discharge is then given by the discrete linear convolution

$$Q(t) = \sum_{i=0}^{t} \sum_{j=1}^{M} q(t-i,j)\ a(t-i,j)$$

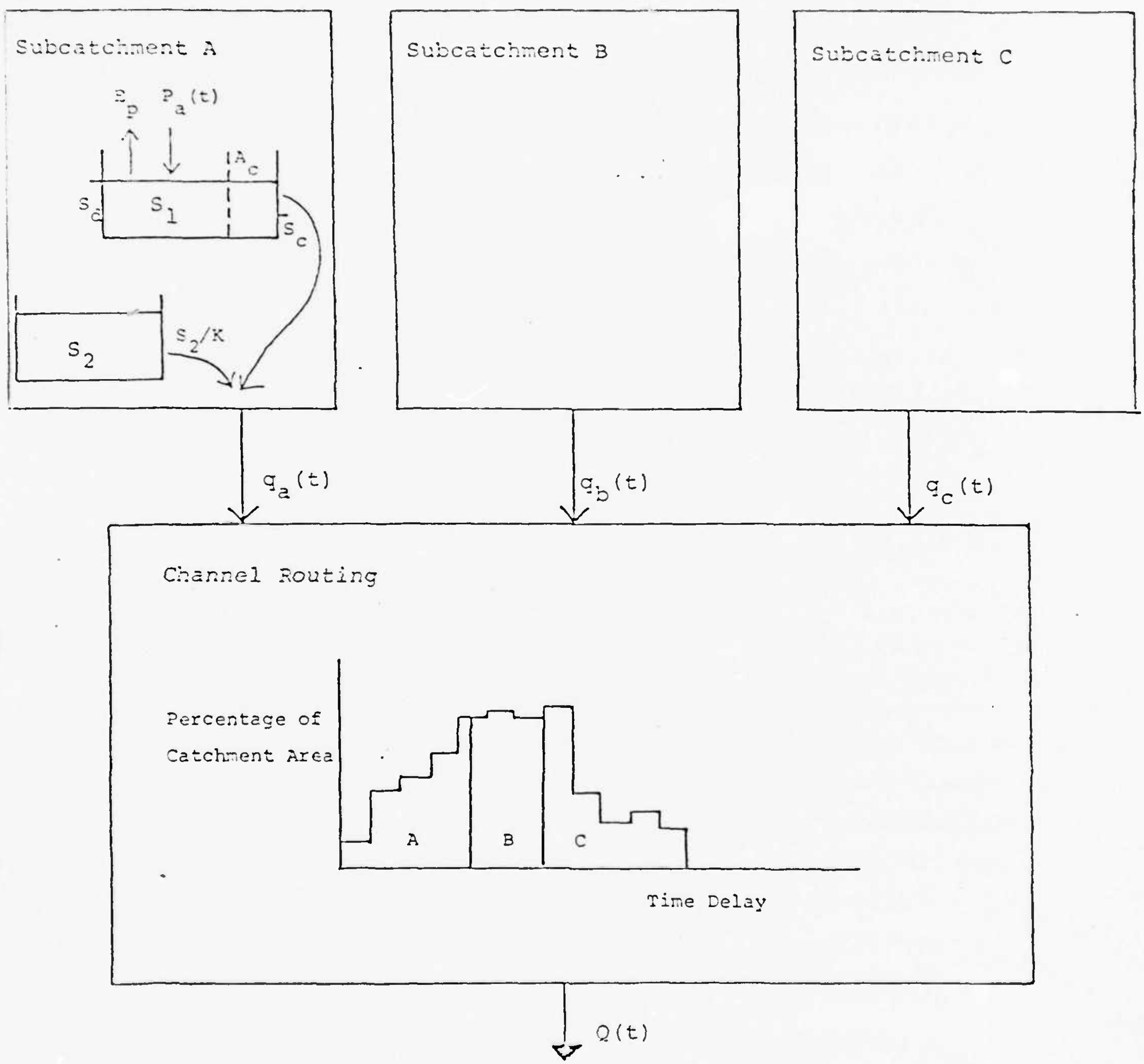


Figure 4. The rainfall/runoff model.

where $Q(t)$ is catchment discharge at time t, M is the number of subcatchments, $q(t,j)$ is the predicted discharge from subcatchment j at time t, and $a(t,j)$ is the fractional catchment area in subcatchment j having a travel time t to the catchment outlet.

The number of subcatchments is arbitrary and could have been made equal to the number of raingage input records available. However, three subcatchments have been used in the present study to be compatible with the threshold procedure described above. It was felt that three subcatchments would retain sufficient representation of the spatial pattern of precipitation but has the advantage that the computing requirements in running the model during the calibration phase are not too great, and specification of a stochastic rainfall simulation model is greatly facilitated. The three subcatchments were chosen to be equal in area and bounded by lines of equal distance along the channel network (Fig. 5). The definition of the area contributing to each channel reach was very subjective in such flat terrain, but is not crucial to the analysis.

CALIBRATION OF THE RAINFALL/RUNOFF MODEL

A period of 450 hours was used for model calibration. The original rainfall records were lumped into hourly subcatchment averages using Thiessen polygon weights. A model time step of one hour was used. The model has four

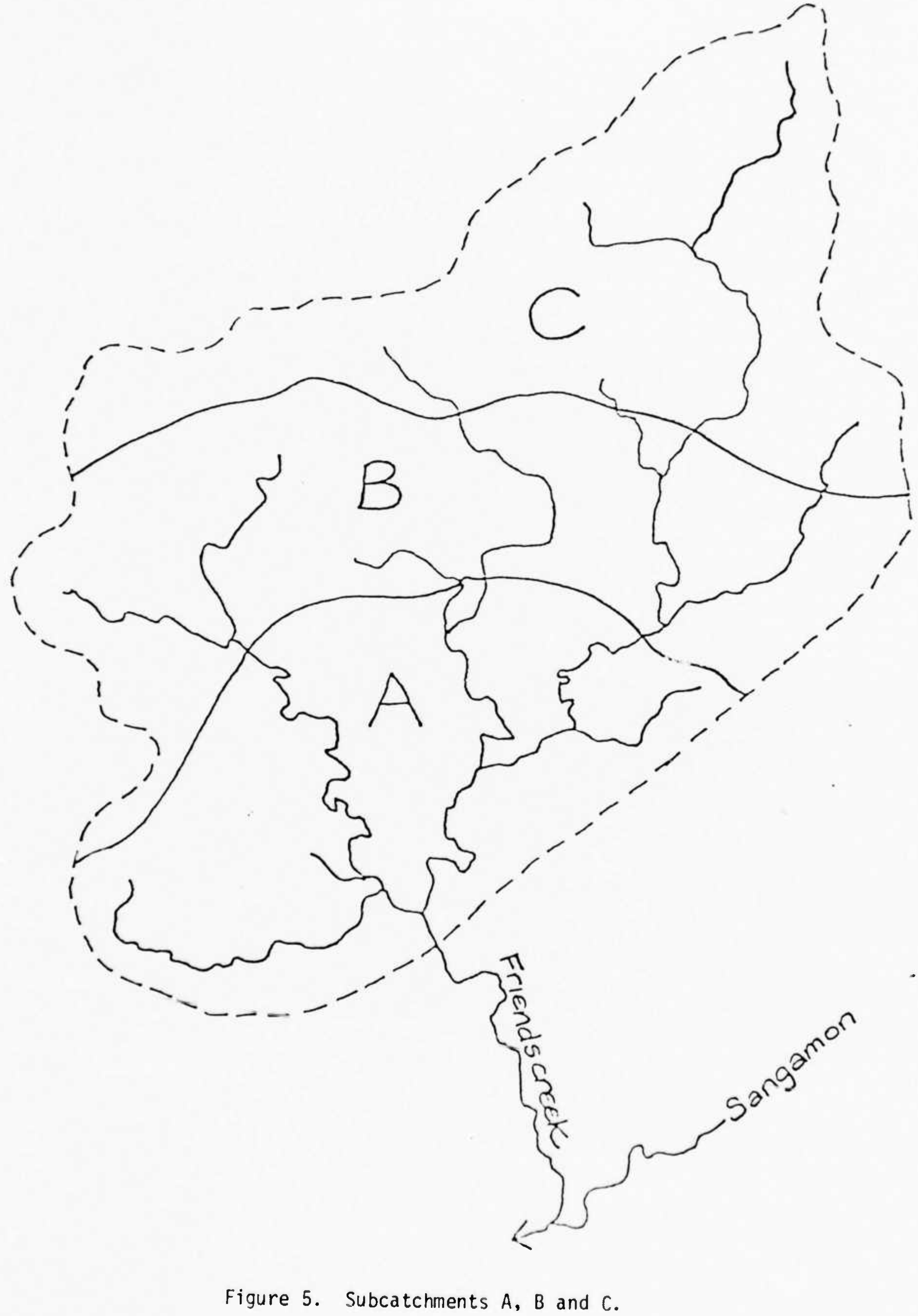


Figure 5. Subcatchments A, B and C.

parameters to be estimated for each subcatchment and one channel routing parameter. In addition the initial conditions at the start of the simulation for each subcatchment must be specified. For simplicity, the parameter values were assumed to be equal for all three subcatchments. After the long dry period preceding the calibration period the store S1 was assumed to be empty. Outflow per unit area from the S2 store was set equal to the observed catchment discharge at the first time step in the record for all three subcatchments. In addition, early trials suggested that the riparian contributing area parameter Ac could be fixed at its initial estimate of 0.02 (the estimated fractional area of channel bed and banks). This left only four parameters to be calibrated (Sc, Sd, K and Cv) and minimized parameter interaction.

The parameters were calibrated using a Rosenbrock automatic optimization procedure available from the Institute of Hydrology modelling package (Douglas, 1974). The optimized values are given in Table 2 and the observed and simulated hydrographs for the calibration period are shown in Fig. 6. The final objective function value gave a modelling efficiency F of 96.4% where

$$\frac{F}{100} = 1 - \frac{\sum_{t=1}^{450} (QOBS(t) - QSIM(t))^2}{\sum_{t=1}^{450} (QOBS(t) - \overline{Q})^2}$$

and $\overline{Q}$ is the mean observed discharge, QOBS(t) is the

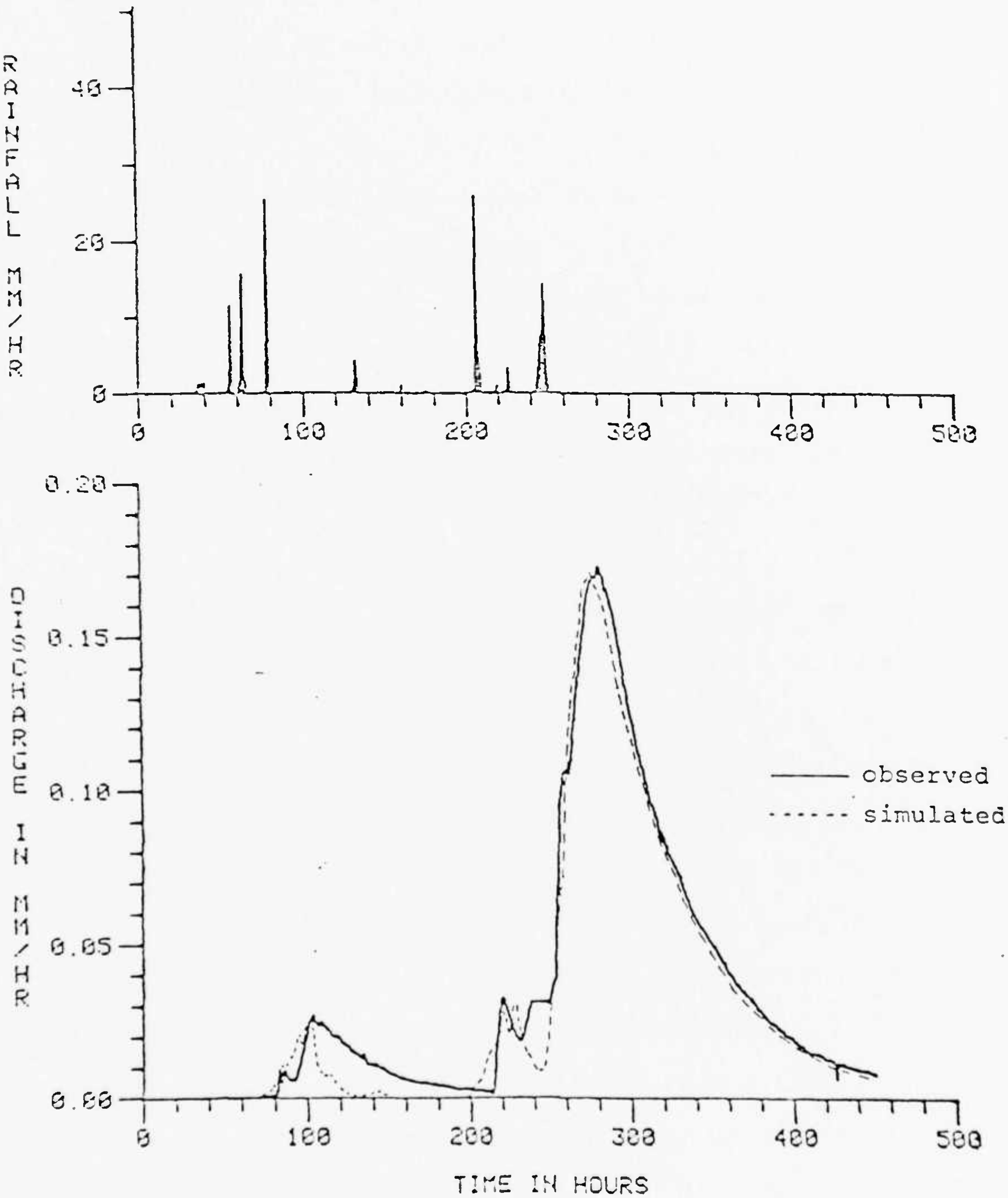


Figure 6. Predicted and observed hydrographs for Friends Creek, summer 1979.

observed discharge and QSIM(t) the simulated discharge at time t. Given the length of record available there was no possibility of doing a split record model validation in this case.

The optimized channel wave velocity in Table 2 may be compared with measured tracer travel times (giving flow velocities) in the upper 23 km of the Sangamon River (of which Friends Creek is a tributary) in Table 3. A channel wave velocity of 0.597 km/hr gives a maximum wave travel time from the furthest headwater of 41 hours and a mean wave travel time (defined by the centroid of the catchment area/travel time distribution) of 19 hours.

The fact that the spatial pattern of precipitation may be important in the storm runoff process is suggested by running the model using the optimized parameter values but with spatially homogeneous inputs. Fig. 7 compares the observed discharge hydrograph with those predicted using the area A input all over the catchment and area C input all over the catchment. These predictions are markedly different from the spatially distributed input prediction of Fig. 6. Of course, the model might have been calibrated using only, say, area A input and a reasonable fit obtained given the relatively short length of record. Our results still demonstrate that the effect of using a non-representative set of gages (relative to calibration) is of considerable importance.

TABLE 2. Calibrated values of model parameters.

SUBCATCHMENT PARAMETERS

A_c	Fractional riparian contributing area	0.02
S_c	S1 store threshold for riparian area	61.49 mm
S_d	S1 store threshold for input to S2	105.60 mm
K	mean residence time in S2 store	56.82 hr

CHANNEL ROUTING PARAMETER

C_v	Wave velocity	0.597 km/hr

TABLE 3. Measured channel flow velocities (after Stall and Hiestand, 1969, for upper 23 km of Sangamon River, origin to Saybrook).

Flow Condition	Approximate Flow Duration Value %	Mean Flow Velocity km/hr
Low	10	0.399
Medium	50	0.532
High	90	0.769

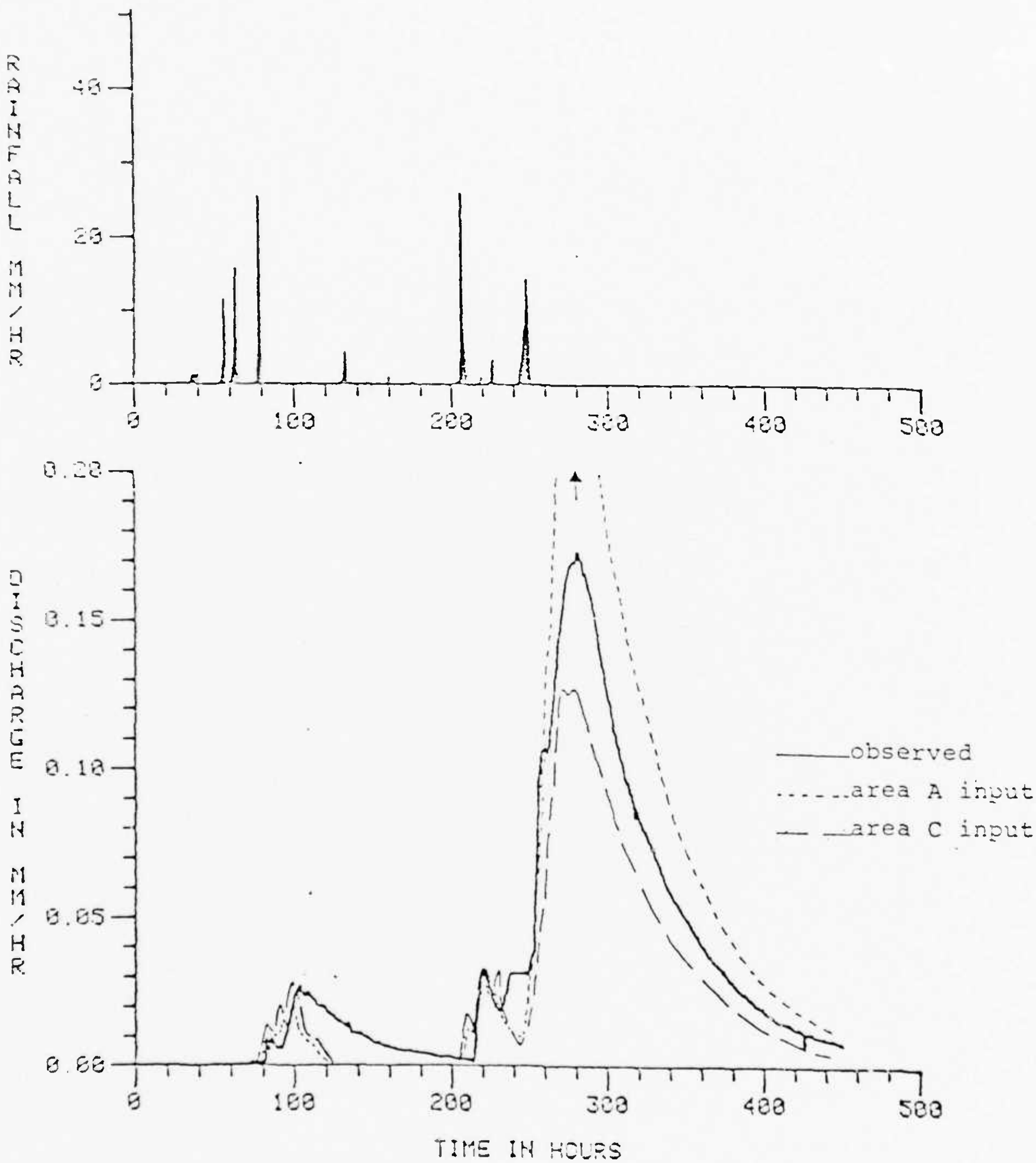


Figure 7. Predicted hydrographs using area A and area C input as a uniform input over the catchment.

RAINFALL MODEL

The 11-year rainfall record from ECIN was used to develop a procedure to generate a synthetic record of precipitation events with statistical properties appropriate for central Illinois. The ECIN network was superimposed over the Friends Creek catchment and Thiessen weights were used to compute rainfall on the three subareas A, B and C. Average depths and durations for each of the three areas in all summers (June, July and August) were determined. Storms with more than 3 showers or with duration greater than 24 hours or with depths less than 0.1" were eliminated from the analysis.

A number of stochastic models for thunderstorm synthesis have been developed (e.g., Sorman and Wallace 1972; Duckstein et al. 1972; Smith and Schreiber 1974; Croley et al. 1978). Rather than employing a sophisticated stochastic rainfall generation model, we chose a simple statistical procedure as consistent with the goals of our study. Storm events were generated independently and the statistical effect of different interstorm time periods was accounted for by choosing initial conditions for the S2 store of the runoff model from an exponential distribution representing the range of initial (pre-storm) discharges observed in the Goose Creek and Friends Creek records (Figure 9). Lacking further information the initial value of the S1 store was taken from a uniform distribution with

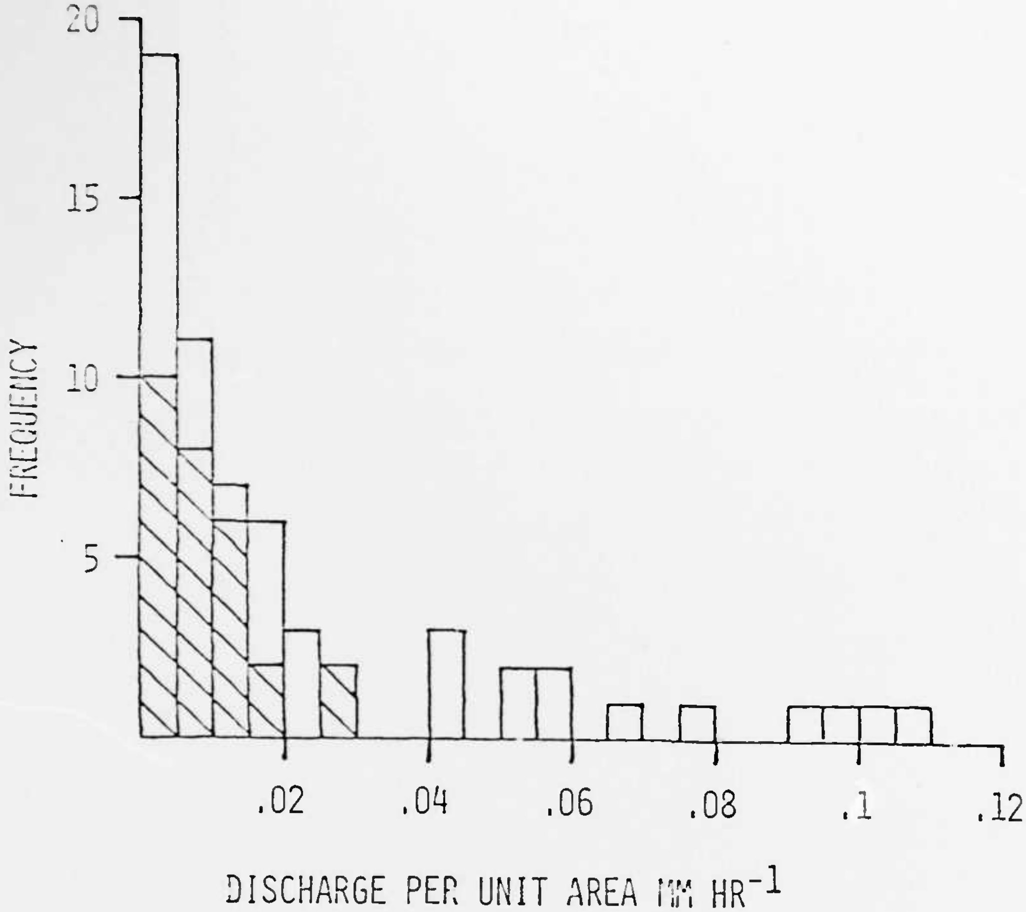


Figure 8. Frequency histogram of initial discharges per unit prior to storm hydrographs. Combined Goose Creek and Friends Creek (shaded) data.

the range $(0, S_d)$.

The rainfall generation scheme must produce 1) total depth, 2) duration, 3) spatial pattern and 4) temporal distribution. The first three items were selected from a multivariate log-normal distribution. A scatter diagram of depths and durations of storms for area B suggested that a logarithmic transformation of the data would be appropriate. Fig. 9 shows the frequencies of log values of these quantities. Spatial pattern was preserved by the use of depth "multipliers" for A/B and C/B. That is, the ratios of storm depths for area A to area B and area C to area B were calculated for each summer storm. Rainstorms, including spatial pattern, can then be simulated (statistically) by choosing depth and duration for area B and the A/B and C/B multipliers from an appropriate distribution. Depth for area A, for example, is then calculated simply as the product of multiplier A and the depth for area B. A sample of the observed storm multipliers is plotted in Fig. 10 and the histograms of log values are shown in Fig. 11. The means and the variance-covariance matrix for log values of depth, duration, multiplier A and multiplier C are listed in Table 4. Although the hypothesis that the storm depth and the multipliers came from a log-normal distribution, can be rejected at the 95% level by a Chi square goodness-of-fit test, practical considerations for generation of correlated random variables dictated use of a multivariate log-normal

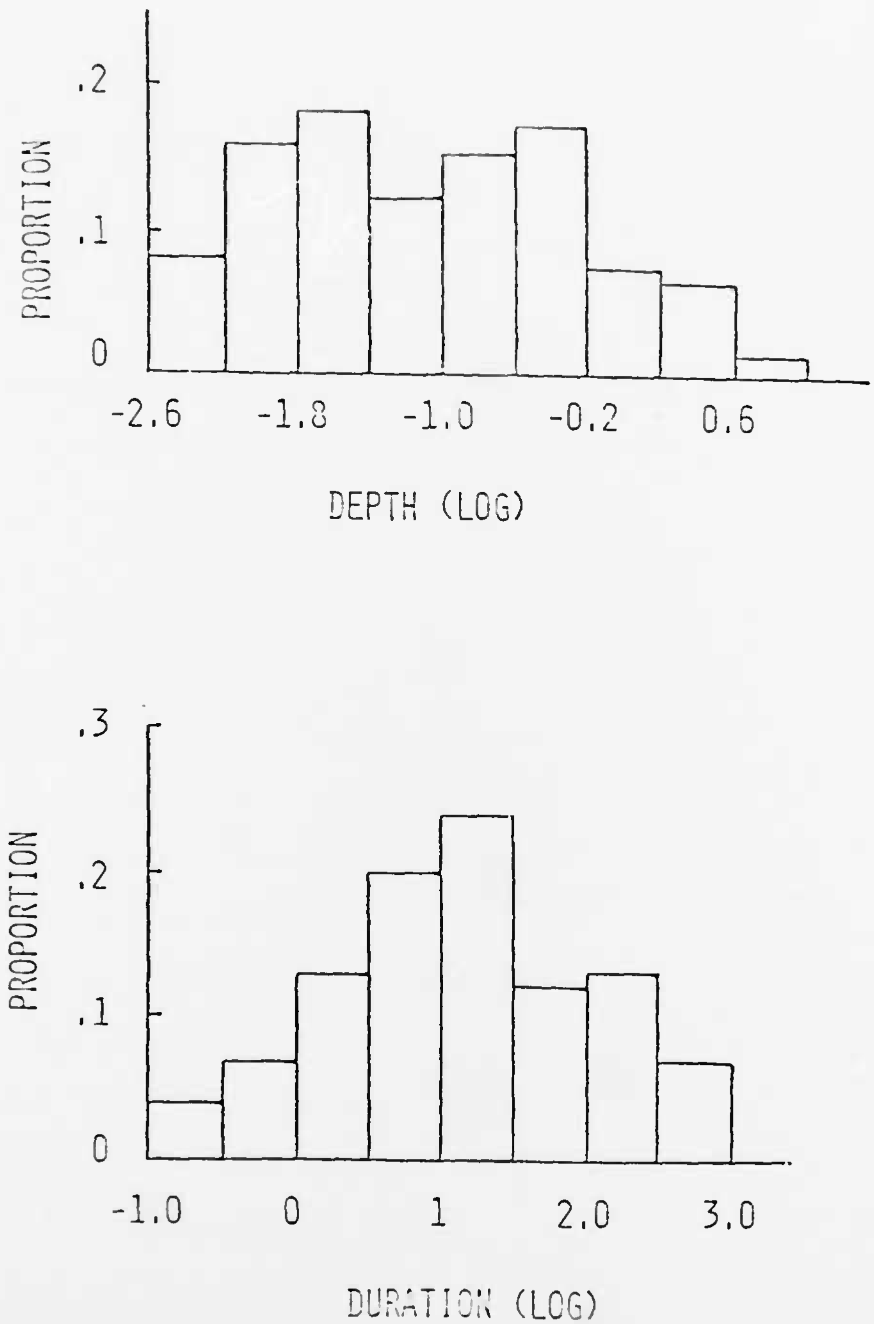


Figure 9. Frequency histograms of log values of depth and duration.

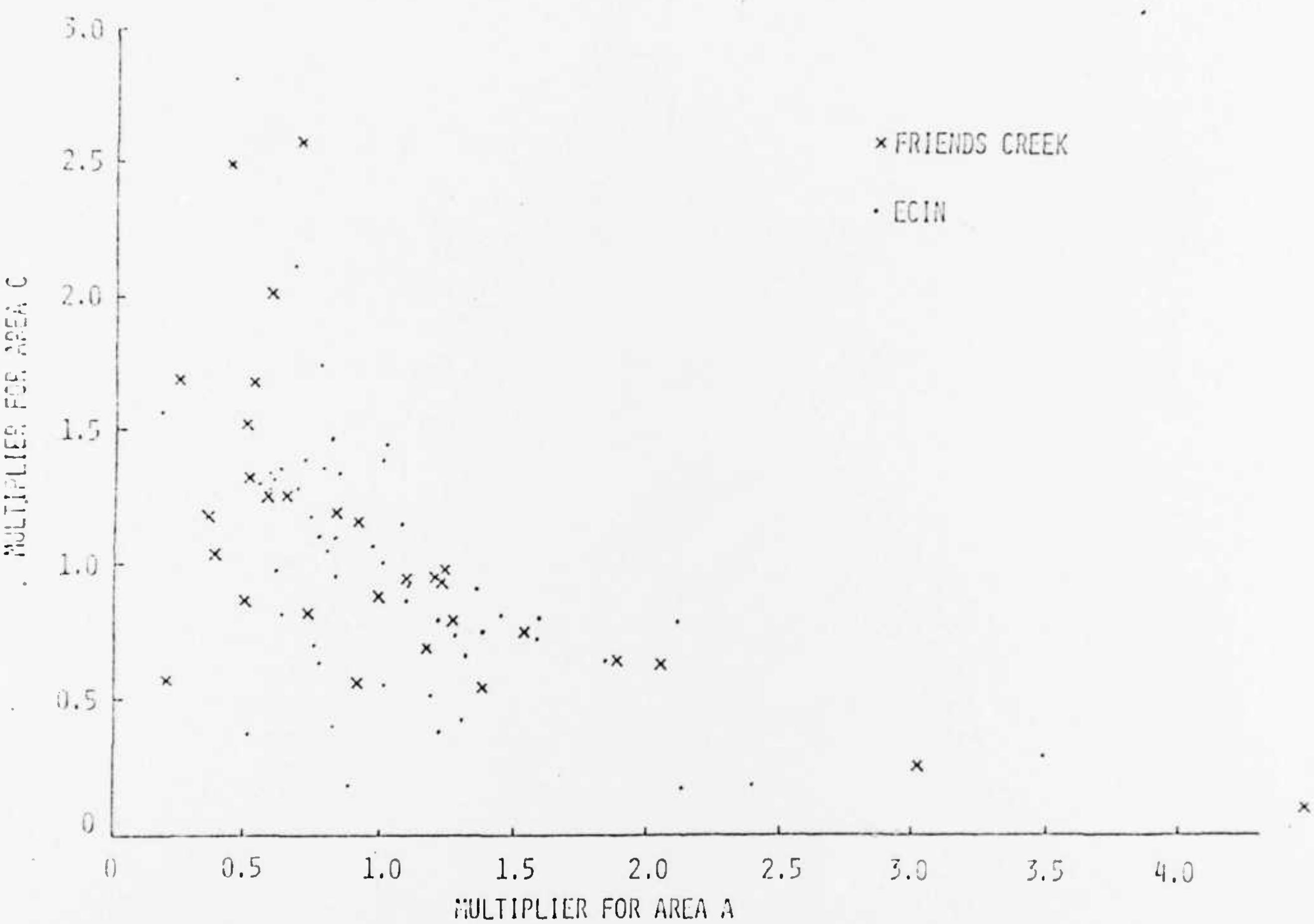
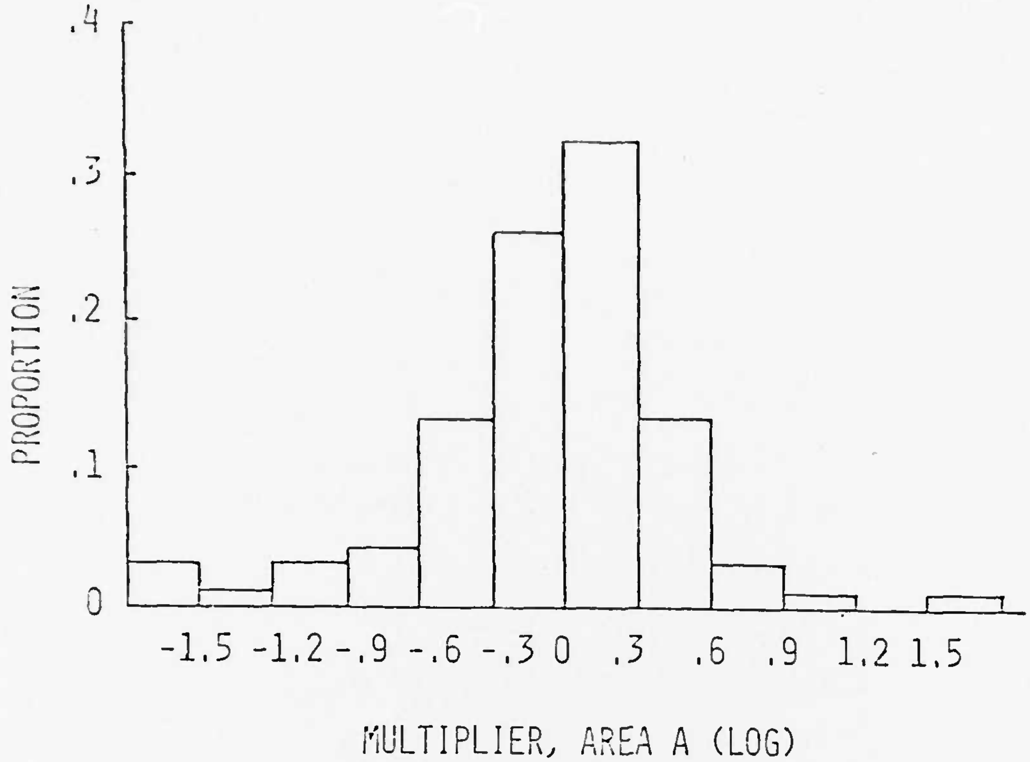


Figure 10. Storm multipliers for area A and for area C.



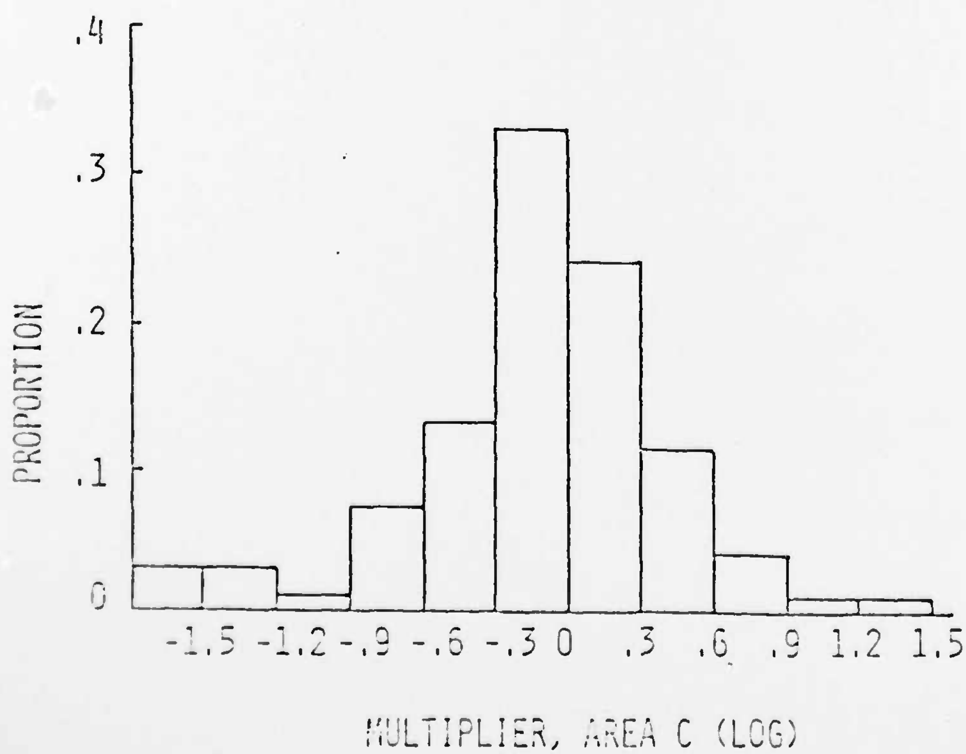


Figure 11. Frequency histograms of log values of storm multipliers.

distribution. We do not think that our general conclusions depend strongly on this assumption.

Time distributions of rainfall were derived from the normalized cumulative precipitation curves for thunderstorms presented by Huff (1967). Storms were assigned to one of the four types of hyetographs shown in Fig. 12 according to the following probabilities: type I, 0.37; type II, 0.39; type III, 0.20; type IV, 0.04.

Daily evaporation was modelled as a normally distributed random variable independent of rainfall. Data for summer, 1979 showed no significant difference between evaporation on rain *vs* no-rain days.

SIMULATION RESULTS

One thousand storms were generated using the statistical procedure described above. This represents a sample of approximately 75 to 100 years based upon the observed ECIN network statistics. The threshold analysis as previously described was applied to the synthetic record and storms were classified as either concentrated on the upper basin (category I), concentrated on the lower basin (category II) or relatively uniform (category III). Hydrographs were simulated for the storms in each class and peak discharge, time to peak and total storm volume were noted.

The potential for isolating the effects of spatial rainfall patterns from other uncertainties can be gaged by

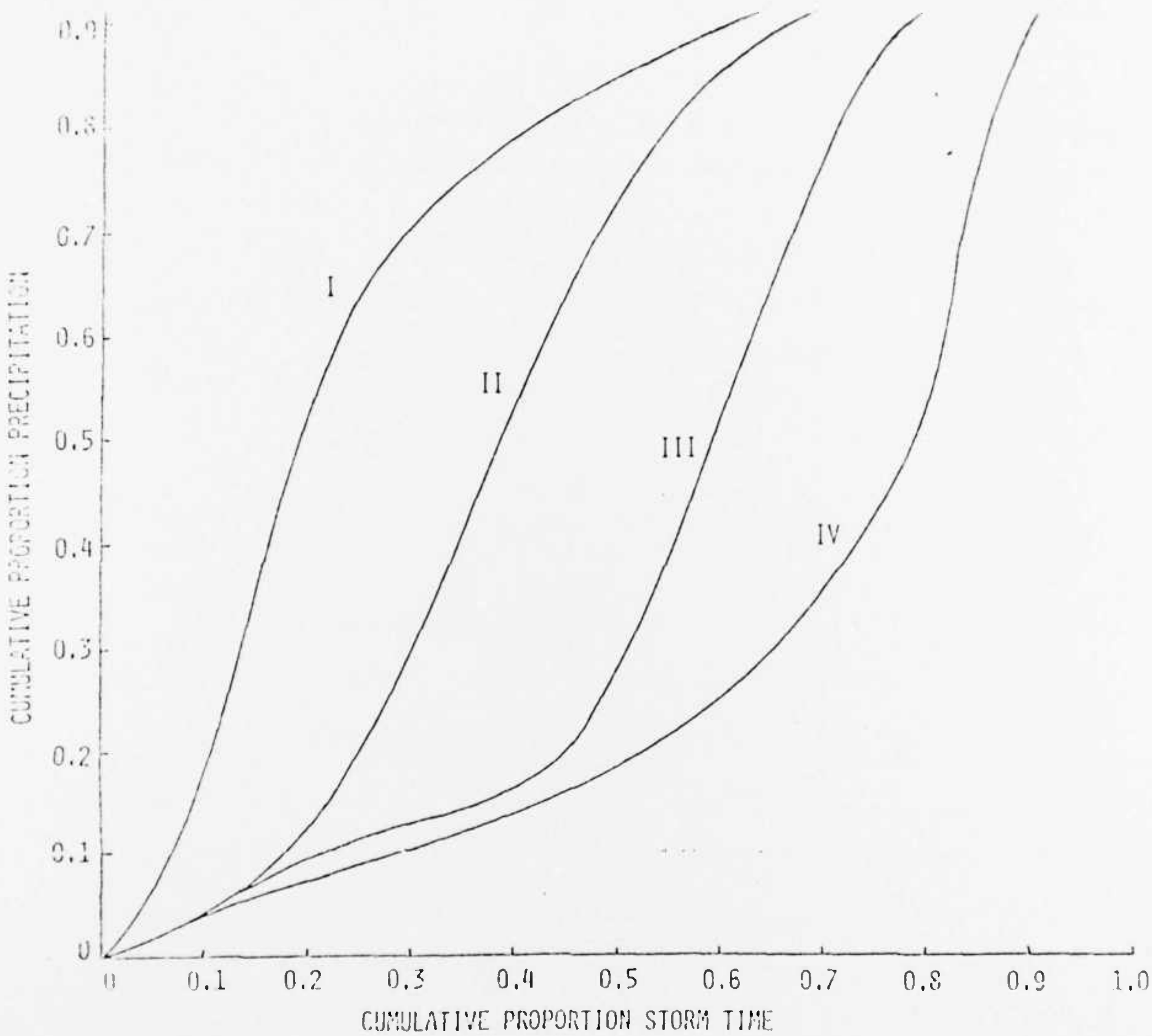


Figure 12. Normalized hyetographs for four storm types (after Huff, 1967).

TABLE 4. Statistics for log values of depth, duration, multiplier A and multiplier C.

Mean Values

Depth	-1.084
Duration	1.104
Multiplier A	-0.093
Multiplier C	-0.144

Variance-Covariance Matrix

	Depth	Duration	Multiplier A	Multiplier C
Depth	0.637	0.355	0.029	0.057
Duration		0.810	0.109	0.061
Multiplier A			0.276	-0.099
Multiplier C				0.326

TABLE 5. Kolmogorov-Smirnov statistics comparing hydrograph characteristics for the three storm categories

	$d_{m,n}$		
	Category I vs II	Category II vs III	Category I vs III
Peak Flow	0.136	0.178	0.267
Time to Peak	0.767	0.294	0.506
Total Stormflow Volume	0.073	0.087	0.118
95% value of $d_{m,n}$	0.176	0.193	0.199

comparing hydrograph characteristics for the three threshold categories. Table 5 gives the values of $d_{m,n}$, the two-sample Kolmogorov-Smirnov statistic, for the three categories and for the three hydrograph characteristics. The value of d required for rejection of the null hypothesis at the 95% level is also noted. Time to peak discharge is significantly different amongst categories but except for category I peak discharge vs category III peaks, no other differences are significant even with ca. 100 years record. Given that records of length tens of years, let alone 100 years, are not readily available for the type of problem we are considering, a precise answer to the question of how long a record is required was not sought, it suffices to say that a very long record indeed would be necessary.

To compare the importance of spatial rainfall patterns *per se* with the importance of the sampling problem associated with rainfall variability, hydrograph simulations were also prepared using area A and area C precipitation as uniform inputs to the runoff model. That is, hydrographs were simulated as if only data from area A (or area C) were available and as if those data were extrapolated to the entire catchment. Table 6 lists values for the Kolmogorov-Smirnov statistic for comparisons between distributed input simulations and those done with the input approximated as uniform based on either area A or area C. Differences amongst peak discharges, time to peak and total volume are all significantly different for category I, distributed vs area A input, and for category II, distributed vs area C

TABLE 6. Kolmogorov-Smirnov statistics comparing hydrograph characteristics for different inputs in various categories.

	$d_{m,n}$	
	Spatially distributed input *vs* input for area A	Spatially distributed input *vs* input for area C
CATEGORY I		
Peak flow	0.294	0.139
Time to peak	0.749	0.472
Total volume	0.261	0.227
95% $d_{m,n}$	0.197	0.182
CATEGORY II		
Peak flow	0.094	0.245
Time to peak	0.445	0.349
Total volume	0.148	0.243
95% $d_{m,n}$	0.170	0.182
CATEGORY III		
Peak flow	0.074	0.071
Time to peak	0.111	0.079
Total volume	0.086	0.070
95% $d_{m,n}$	0.214	0.215

input. As expected, none of the differences were significant for the category III storm hydrographs. These results are for the entire sequence of storms.

A similar comparison between category I storms - distributed vs area A input - and category II storms - distributed vs area C input with 1/2 of the record length is given in Table 7. Again all characteristics show highly significant differences and we infer that even smaller samples would also show significant differences.

DISCUSSION

The results from the analysis of the deterministic/statistical modeling data indicate that differences in the timing of peak flows are most likely to be discerned as an effect of spatial rainfall pattern. Differences in peak discharges are much less likely to be isolated from a background of other influences. Unfortunately, in real, as opposed to synthetic, streamflow records, peak flows and their timing can be difficult to define unambiguously because of complex hyetograph/hydrograph shape. This fact may make the problem of discerning effects of rainfall pattern even more difficult than suggested by this study.

On the other hand, storm movement, which was neglected in our study, might accentuate effects of spatial pattern in some instances. For the Friends Creek catchment differences in the timing of summer thunderstorms are small compared to

TABLE 7. Kolmogorov-Smirnov statistics comparing hydrograph characteristics for category I storms (distributed vs area A inputs) and for category II storms (distributed vs area C inputs) for half of the total record length.

	Distributed vs area inputs
CATEGORY I	
Peak flow	0.316
Time to peak	0.772
Total volume	0.305
95% $d_{m,n}$	0.279
CATEGORY II	
Peak flow	0.336
Time to peak	0.333
Total volume	0.276
95% $d_{m,n}$	0.257

the channel time of travel and consequently our results are unlikely to be affected by sophistication of the rainfall modelling procedure. We have also neglected several other factors that might accentuate the effects of rainfall pattern under certain conditions, for example spatial differences in catchment response, spatial differences in antecedant conditions and diffusion within the channel network. Much more comprehensive discharge records and channel data would be required before such effects could be studied. Our results suggest that only in cases where such effects were particularly marked would rainfall pattern have a significant effect on peak flows and storm runoff volumes.

Although the effects of rainfall pattern per se may not be striking, the analysis of the sampling problem indicates that significant differences in predicted peak discharge will result in cases where a "non-representative" subsample of raingages is used to provide input to the model. Thus, we conclude, as did Dawdy and Bergman (1969) and Wilson et al. (1978), that an accurate portrayal of spatial variation in rainfall is a prerequisite for accurate simulation of streamflows.

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REFERENCES

Chow, V. T. 1978. Stochastic modeling of watershed systems. In: Chow, V. T. (ed.) Advances in Hydroscience, vol. 11, pp. 1-93.

Croley, T. E., II, Eli, R. N., II and J. D. Cryer. 1978. Ralston Creek hourly precipitation model. Wat. Resour. Res. 14: 485-490.

Dawdy, D. R. and J. M. Bergmann. 1969. Effect of rainfall variability on streamflow simulation. Wat. Resour. Res. 5: 958-966.

Douglas, J. R. 1974. Conceptual modelling in hydrology. Rept. No. 24, Inst. of Hydrology, Wallingford.

Duckstein, L., Fogel, M. M. and C. C. Kisiel. 1972. A stochastic model of runoff-producing rainfall for summer type storms. Wat. Resour. Res. 8: 410-421.

Huff, F. A. 1967. Time distribution of rainfall in heavy storms. Wat. Resour. Res. 3: 1007-1019.

Huff, F. A. 1968. Spatial distribution of heavy storm rainfalls in Illinois. Wat. Resour. Res. 4: 47-54.

Kirkby, M. J. 1976. Tests of the random network model and its application to basin hydrology. Earth Surf. Proc. 1: 197-212.

Phanartzis, C. A. 1972. Spatial variability of precipitation in the San Dimas Experimental Forest and its effect on simulated streamflow. Tech. Rept. 11, Hydrology and Water Resources, Univ. of Ariz., Tucson.

Smith, R. E. and H. A. Schreiber. 1974. Point processes of seasonal thunderstorm rainfall 2. Rainfall depth probabilities. Wat. Resour. Res 10: 418-423.

Sorman, V. A. and J. R. Wallace. 1972. Digital simulation of thunderstorm rainfall. Rept. ERC-0972, Environ. Resour. Ctr., Ga. Inst. Tech., Atlanta.

Stall, J. D. and D. W. Hiestand. 1969. Provisional time-of-travel for Illinois streams. Rept. of Investigation 63, Illinois State Wat. Surv., Urbana.

Surkan, A. J. 1969. Synthetic hydrographs: effects of network geometry. Wat. Resour. Res. 5: 112-128.

Wilson, C. B., Valdes, J. B. and I. Rodriguez-Iturbe. 1978. On the influence of the spatial distribution of rainfall on storm runoff. Wat. Resoure. Res. 15: 321-328.

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